

# Tree size, microhabitat, and hydraulic traits (interactively) shape drought response in a temperate broadleaf forest

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## Abstract

Predicting forest responses to drought is an increasingly critical task under climate change effects. Part of the problem is due to the lack of studies analyzing the confluence of leaf hydraulic traits with biophysical parameters. In this study, we analyze the interaction between these two trait groups using forest census data from a 25.6-ha ForestGEO plot in Virginia (USA). Drought periods were defined by both Palmer Drought Severity Indices (PDSI) and their identification from tree-ring records for 12 species representing 97% of woody productivity. Each drought scenario (1964-66, 1977, 1999), along with the overall trend, was then tested against leaf hydraulic trait measurements and microhabitat biophysical data. Individual-level growth responses to the three individual droughts were stronger among taller trees in dominant canopy positions, those in wetter microsites, and for more drought-sensitive species as assessed by leaf traits (turgor loss at less negative leaf water potential, greater shrinkage with leaf dehydration), with substantial variation in the best predictor variables across given droughts. We conclude that when droughts occur, large dominant trees, drought-sensitive species, and individuals in wetter microhabitats are likely to be most strongly affected.

## Introduction

Understanding how and why trees respond to drought is critical to predicting forest drought responses and climate change feedbacks. (1 paragraph on this- I have lots of content on this and will add later.)

[Understanding forest responses to drought requires increased functional understanding of the factors that confer individual-level vulnerability or resistance.] Forests are diverse in terms of tree sizes and functional traits, and it is known that trees varying in size and functional traits respond differently to drought (e.g., (Bennett et al., 2015); REFS). Therefore, in order to understand whole-forest response to drought, we need a functional understanding of how responses vary by tree size, microhabitat, and species. There are 3 fundamental questions that must be addressed:

*First, what drives the observed tendency for large trees to suffer more during drought?*

Bennett et al. (2015) showed that in forests globally, large trees suffer greater growth reductions during drought. However, this analysis quantified tree size based on DBH, which has no direct mechanistic meaning. This study proposed two major mechanisms (besides insects) for the observed greater drought growth reductions of large trees: (1) inherently greater biophysical challenge of being tall; (2) greater exposure of the crowns of large trees. Counteracting these effects, (3) the larger root systems of larger trees may confer an advantage in terms of allowing greater access to water, but it appears that this effect is usually insufficient to offset the costs of height and/or crown exposure.

Canopy trees have lower drought resistance because they are exposed to higher solar radiation, greater wind speeds, and lower humidity. Alternatively, the generally suppressed status of subcanopy trees may be insufficient to override the benefits of their buffered environment during drought.

*Second, how do species' traits - alone and in interaction with tree size - influence drought response?* Analyzing drought responses on the species level does not fully explain mechanisms and is not feasible in diverse forests. The solution is a trait-based approach. Leaf hydraulic traits hold more promise than more commonly/traditionally-measured traits such as wood density and specific leaf area (SLA) (Medeiros et al. 2019).

Commonly measured traits including wood density (REFS), leaf mass per area (Abrams, 1990) (Guerfel et al., 2009), and ring porosity (Elliot et al. 2015, Friedrichs et al. 2009) have been linked to drought responses and likely correlated with drought resistance in this forest. However, we hypothesize that leaf hydraulic traits such as leaf area shrinkage upon dessication (PLA) and turgor loss point (TLP), which are emerging as potentially more informative traits but whose effect on drought resistance has never been tested (CONFIRM), will prove better predictors.

Moreover, there may be an interaction between traits and tree size. It is possible that the pattern observed by Bennett et al. (2015) could be caused by smaller trees being more drought resistant. Alternatively, larger trees may have more drought-resistant traits as adaptations to greater biophysical challenges.

*Third, are responses similar or variable across individual drought years?* Droughts are rarely explicitly defined in ecological studies (Slette et al., 2019), yet no two droughts are the same.

We need to understand the factors confirming drought vulnerability or resistance not only for extreme droughts with dramatic impacts on tree growth and mortality, which tend to dominate the literature (Bennett et al., 2015) (REFS), but also for more modest but frequent droughts—e.g., those with historical return intervals on the order of a decade.

Here, we combine tree-ring records covering three droughts (1964-66, 1977, 1999), species functional and hydraulic trait measurements, and forest census data from a 25.6-ha ForestGEO plot in Virginia (USA) to test a series of hypotheses and associated specific predictions (Table 1) designed to yield functional understanding of how tree size, microenvironment, and species' traits collectively shape drought responses. First, we focus on the role of tree size and its interaction with microenvironment. We confirm that, consistent with most forests globally (Bennett et al., 2015), larger-diameter trees have lower drought resistance in this forest, which is in an ecoregion represented by only one study in Bennett et al (2015) (H1.0). We then test hypotheses designed to disentangle the relative importance of tree height (H1.1), crown exposure (H1.2), and root water access, which should be greater for larger trees in dry but not perpetually wet microsites (H1.3). Second, we focus on the role of species' functional and hydraulic traits and their interaction with tree height. We hypothesize that drought resistance will follow predicted and observed patterns in relation to wood density, specific leaf area, and ring porosity (P2.1a-c), but that leaf hydraulic traits such as leaf area shrinkage upon dehydration and turgor loss point will prove better predictors (P2.1d-e). We then test whether these traits correlate with tree height (P2.2), potentially driving the observed tendency for taller trees to suffer more during drought (P2.3). Finally, we focused on variability among droughts, asking how community resistance varied across droughts (H3.1) and whether the factors confirming vulnerability or resistance varied across droughts (H3.2).

*Let's put Table 1 here. We need to give the hypotheses/ predictions here. It seems counterintuitive to put the results right up front like that, but it actually tends to be a higher-impact style of writing, and recommended here.*

## Methods

*Study site* Research was conducted at the 25.6 ha ForestGEO (Global Earth Observatory) study plot at the Smithsonian Conservation Biology Institute (SCBI) in Virginia, USA (38°53'36.6"N, 78° 08'43.4"W) (Anderson-Teixeira et al., 2015a). SCBI is located in the central Appalachian Mountains at the northern edge of Shenandoah National Park. Elevations range from 273-338m above sea level (Gonzalez-Akre et al., 2016) with a topographic relief of 65m (Bourg et al., 2013). Dominant species include *Liriodendron tulipifera*, oaks (*Quercus* spp.), and hickories (*Carya* spp.).

*Data collection and preparation* The SCBI ForestGEO plot was censused in 2008, 2013, and 2018 following standard ForestGEO protocols, whereby all free-standing woody stems  $\geq 1$ cm diameter at breast height (DBH) were mapped, tagged, measured at DBH, and identified to species (Condit, 1998). From this census data, we used measurements of DBH from 2008 to calculate historical DBH (described below), along with tree location in the plot to determine the topographic wetness index. Furthermore, we used data for all stems  $\geq 10$ cm to analyze functional trait composition relative to tree height. *I added the last sentence—*

*not sure if you've described that below yet. I don't think you need to note here which data we use, so long as that's described in the portions where you describe the analysis.*

We analyzed tree-ring data from the twelve species contributing most to woody aboveground net primary productivity (ANPP), which together comprised 97% of study plot ANPP between 2008 and 2013 (Helcoski et al., 2019). Cores were obtained in 2010-2011 or 2016-2017 from a breast height of 1.3m using a 5mm increment borer. In 2010-2011, cores were collected from randomly selected live trees of species with at least 30 individuals of DBH  $\geq 10$ cm (Bourg et al., 2013). In 2016-2017, cores were collected from all trees found dead in the annual mortality census (Gonzalez-Akre et al., 2016). Cores were sanded, measured, and cross-dated using standard procedures, as detailed in (Helcoski et al., 2019). The resulting chronologies have been published in association with Helcoski et al. (2019): (ITRDB; GitHub/Zenodo). *is this a database? Yes. Ryan submitted the data but I don't think its posted yet. We should also cite GitHub/Zenodo here. I'll come back to that.*

Height measurements ( $n=\#$  trees) were taken by several researchers between 2012 to 2019, and are archived in a public GitHub repository. Measurement methods included manual (Stovall et al., 2018a, NEON), digital rangefinders (Anderson-Teixeira et al., 2015b), and automatic LiDAR (Stovall et al., 2018b). Rangefinders either used the tangent method (Impulse 200LR, TruPulse 360R) or the sine method (Nikon ForestryPro) for calculating heights. The associated errors for using either method were acknowledged (Larjavaara and Muller-Landau, 2013). Species-specific height allometries were developed (Table S# - **ADD THIS TABLE TO SI**). For species that didn't have enough height measurements, heights were calculated from equations derived from all species in the study.

For each tree, we combined tree-ring records and allometric equations of height and bark thickness to retroactively calculate DBH and estimate height for the years 1950-2009. Prior DBH was estimated using the following equation, using 2008 as the earliest year for having reliable DBH measurements:

$$diamYEAR = dbh2008 - 2*(bark.depth2008) - 2*\Sigma(ring.widthYEAR : ring.width2008) + 2*(bark.depthYEAR)$$

Here, *ring.width* was measured from cores. Bark thickness was estimated from species-specific allometries based on the bark thickness data of (Anderson-Teixeira et al., 2015b). Specifically, we used linear regression equations on log-transformed data to relate bark thickness to DBH (Table S#- **create table to give these equations in SI**) and then used these to estimate bark thickness based on DBH.

Crown positions were recorded in the field during the growing season of 2018 following the crown position protocol from (Jennings et al., 1999), whereby positions were ranked as dominant, codominant, intermediate, or suppressed. As there was no way to retroactively estimate crown position, we assumed that 2018 crown position was reflective of each tree's position over the past 60 years. While some trees undoubtedly changed position, an analysis of crown position relative to height (Fig. XX) and height change since 1959 indicated that change was likely slow. **[work on this— provide details?]**

Topographic wetness index (TWI) was calculated using the (Metcalf et al., 2018) package in R.

Hydraulic traits were collected from SCBI and are summarized in Table 1. In August 2018, we collected leaf samples from three individuals of each species ... **(Nobby's description of methods for the following)**  
1. PLA 2. LMA 4. Wood density 5. TLP

**Table 2. Species analyzed here, listed in descending order of ANPP\_stem. n cores and DBH range represented, and species traits** [\*This replaces/combines the two remaining tables in this section. Suggested columns, with those to include only if they fit in parentheses: species, (stems  $\geq 10$  cm per ha in plot), (ANPP\_stem), n cores, DBH range of cores, (n cores in each crown position) species means for each trait]

sp	n_cores	dominant	co-dominant	intermediate	suppressed	prior dead
caco	13	NA	2	5	5	1
cagl	31	1	8	16	5	1
caovl	23	4	5	12	2	NA
cato	13	NA	NA	6	2	5
fagr	80	NA	7	48	25	NA
fram	62	NA	17	19	14	12
juni	31	NA	21	8	NA	2
litu	98	9	29	25	30	5
qual	61	4	34	20	3	NA
qupr	59	1	26	20	12	NA
quru	69	6	36	23	2	2
quve	77	6	46	22	1	2

Trait	Unit	mean	min	max
Ring Porosity	ring, semi-ring, diffuse	NA	NA	NA
Percent Leaf Area	%	15.09	8.52	24.64
Leaf Mass Area	g/m2	53.50	30.68	75.80
Wood density	g/cm3	0.70	0.40	1.09
TLP	MPa	-2.36	-2.76	-1.92

*Climate and drought years* [add description of climate data used in Fig. 1, NEON vertical profiles]

To accurately understand climate sensitivity, this study used a specific definition of drought, which is not a common practice (Slette et al., 2019). We used the pointRes package (van der Maaten-Theunissen and van der Maaten, 2016) in R (version 3.5.3) to determine drought periods based on trees' drought resistance, which is defined by (Lloret et al., 2011) as the ratio between the performance during and before the disturbance. Candidate drought years were defined if >50% of the cored trees experienced <30% growth in a year compared to the previous 5 years. These were then cross-validated with the regional Palmer Drought Severity Index (PDSI) values for each year, which yielded a set of three periods that were consistently shown as drought: 1964-1966, 1977, and 1999.

**Figure 1. Time series of peak growing season (May-August) climate conditions and residual chronologies for each species.** Droughts analyzed here are indicated by dashed lines, and shading indicates the pre-drought period used in calculations of the resistance metric. Figure modified from (Helcoski et al., 2019).

## Results

**Table 1. Summary of hypotheses, predictions and results** We count predictions as fully supported (or rejected) when the direction of response matches (or contradicts) the prediction. H2.3-H3.2 are based on if models containing species traits in H2.1 had  $dAIC \geq 2$  relative to the appropriate null model or to any alternative multivariate model within 2  $dAIC$ . Parentheses indicate that predictions were partially supported (or rejected). In other words, parentheses indicate when the direction of response matched (or contradicted) the prediction in some but not all models with  $dAIC < 2$  relative to the appropriate null model. With categorical variables such as crown position, a "(yes)" notation describes when the trend matched the prediction, but it wasn't significant A "(yes/no) or ("no/yes)" indicates tendencies in opposite directions in univariate tests versus the best full models, respectively. "(yes) (Table 1.xlsx)

trying to test how the negative effect of height is caused by the traits,

(no) means there's a trend in the expected direction but not consistently significant

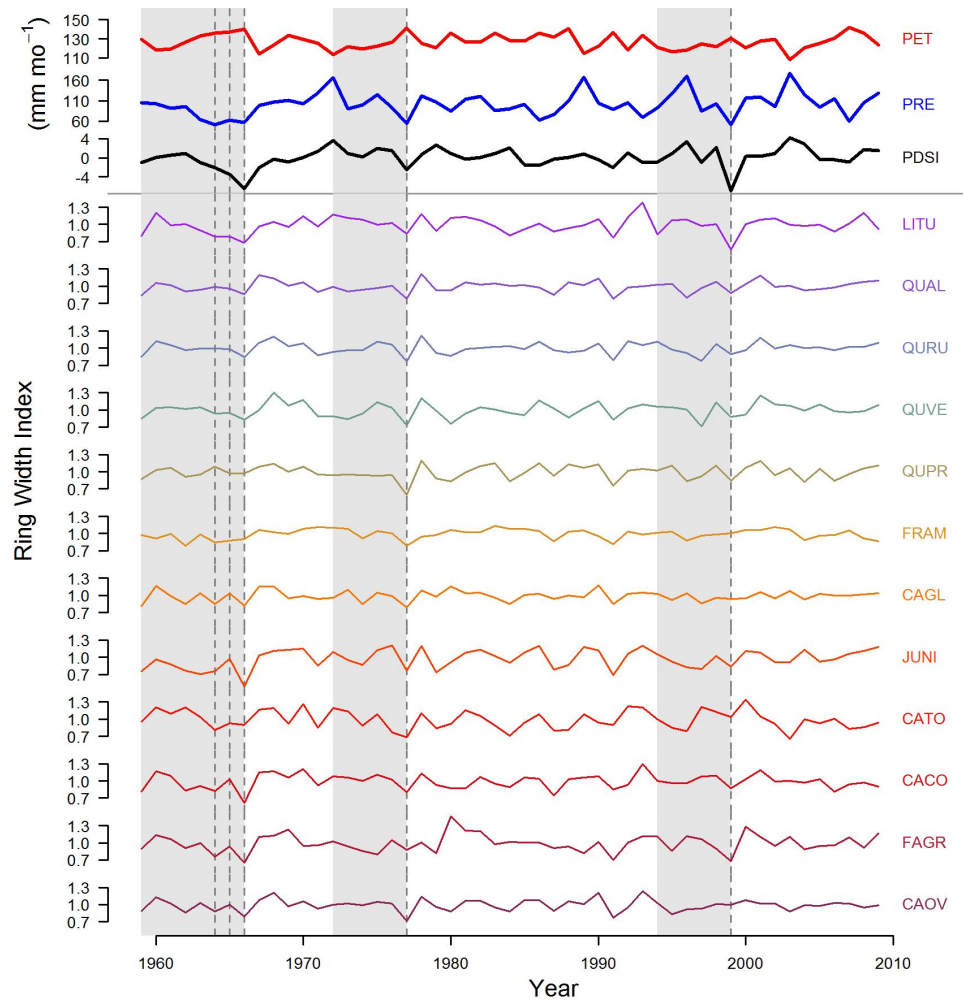


Figure 1: Time series of combined tree cores by species

Prediction	Overall	Prediction supported?		
		individual droughts		
		1964-66	1977	1999
<i>H1.0. larger-diameter trees have lower drought resistance</i>				
1.0. Drought resistance decreases with DBH	yes	yes	(yes)	(no/yes)
<i>H1.1. Drought resistance decreases with tree height</i>				
1.1a- Drought resistance decreases with height	yes	yes	(yes)	(no/yes)
1.1b- Height is a better predictor of drought resistance than DBH	(yes)	(no)	(no)	-
<i>H1.2. Drought resistance decreases with canopy exposure</i>				
1.2a- Canopy position alone predicts drought resistance (dominant < co-dominant < intermediate < suppressed)	(no)	(yes)	(yes)	(no)
1.2b- After accounting for height, canopy position predicts drought resistance (dominant < co-dominant < intermediate < suppressed)				
<i>H1.3. Drought resistance is linked to rooting volume in drier microhabitats</i>				
1.3- There is a negative interactive effect between tree height and topographic water index				
<i>H2.1. Species traits predict drought resistance</i>				
2.1a - wood density correlates positively to drought resistant	(yes)			
2.1b - leaf mass area correlates positively to drought resistance	(yes)			
2.1c - diffuse porous species are more sensitive than ring porous	(yes)			
2.1d -leaf area shrinkage upon dessication (PLA) is negatively correlated with drought resistance	yes			
2.1e - TLP correlates negatively with drought resistance	yes			
<i>H2.2. More drought-resistant traits associated to taller trees</i>				
2.1a - community mean wood density correlates positively to height	?	-	-	-
2.1b - community mean leaf mass per area correlates positively to height	?	-	-	-
2.1c - community fraction of diffuse porous species decreases with height	?	-	-	-
2.1d - community mean leaf area shrinkage upon dessication (PLA) is negatively correlated with height	no?	-	-	-
2.1e - community mean TLP correlates negatively with height	no?	-	-	-
<i>H2.3. Size-dependent drought resistance is driven by functional traits</i>				
2.3. Inclusion of traits in the statistical model eliminates effect of height	no			
<i>H3.1. Responses varied by drought</i>				
3.1. Drought year explained variation in drought resistance	yes			
<i>H3.2. Predictor variables varied across droughts.</i>				
3.2a. Directions of responses to predictor variables is consistent	(yes)	-	-	-
3.2b. Set of predictor variables in best model varies across droughts	yes	-	-	-

Figure 2: Table 1

H2.3 if the effect is negative and is in every top model ( $< dAIC_2$ ), that would be “yes.” if the effect is negative mostly

Once the data was collected, linear mixed models were run following the order of the hypotheses as seen in Figure ??? [individual\_tested\_traits]. Using the (van der Maaten-Theunissen and van der Maaten, 2016) package, we set up models with the resistance value as the response variable, and each prediction’s variable as the independent variable. Variables’ importance in predicting drought tolerance was calculated from mixed-effects models and the lowest AICc (Bates et al., 2019, Mazerolle and portions of code contributed by Dan Linden. (2019)). Null models were determined in order of the predictions. First, we analyzed the combined scenario to determine if “year” was significant. Upon establishing this, we tested height and DBH as size parameters. Although both were significant, height was kept due to its larger delta AICc compared with the null model. We then tested the remaining biophysical and hydraulic traits individually against a null model containing height and year. This yielded Figure ??? (cand\_full). All variables with  $dAICc > 2$  were used as candidates for each scenario’s best model (figure ??? (tested\_traits\_best))

Table 1: All variables tested for climate sensitivity against appropriate null models, in line with hypothesis predictions. Each variable was tested for each drought scenario excepting "year"

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prediction	variable	variable_description	null_model	null_model_year	dAIC_all	co
3.1	year	drought.year	(1 sp/tree)	(1 sp)	35.834	-
2.1	dbh.ln.cm	ln[DBH]	year+(1 sp/tree)	(1 sp)	7.411	-
2.2	height.ln.m	ln[height]	year+(1 sp/tree)	(1 sp)	7.591	-
2.3	position_all	crown.position alone	year+(1 sp/tree)	(1 sp)	-1.460	-
1.2	position_all	crown.position w/height	height.ln.m+year+(1 sp/tree)	height.ln.m+(1 sp)	1.682	-
1.3	height.ln.m*TWI.ln	ln[height]*ln[topographic.wetness.index]	height.ln.m+TWI.ln+year+(1 sp/tree)	height.ln.m+TWI.ln+(1 sp)	-2.018	-
2.4	TWI.ln	ln[topographic.wetness.index]	height.ln.m+year+(1 sp/tree)	height.ln.m+(1 sp)	2.880	-
3.1	rp	ring.porosity	height.ln.m+year+(1 sp/tree)	height.ln.m+(1 sp)	-3.553	+
3.2	PLA_dry_percent	percent.leaf.area	height.ln.m+year+(1 sp/tree)	height.ln.m+(1 sp)	4.413	-
3.3	LMA_g_per_m2	leaf.mass.area	height.ln.m+year+(1 sp/tree)	height.ln.m+(1 sp)	-1.895	+
3.4	mean_TLP_Mpa	mean.turgor.loss.point	height.ln.m+year+(1 sp/tree)	height.ln.m+(1 sp)	4.580	-
3.5	WD_g_per_cm3	wood.density	height.ln.m+year+(1 sp/tree)	height.ln.m+(1 sp)	-2.018	+



Table 2: Candidate variables to be included in full model, chosen by  $\Delta AIC_c > 2$  when individually tested against a null model

prediction	variable	variable_description	top_model
1.2	position_all	crown.position w/height	1999
2.2	height.ln.m	ln[height]	all
2.2	height.ln.m	ln[height]	1966
2.3	position_all	crown.position alone	1966
2.4	TWI.ln	ln[topographic.wetness.index]	all
2.4	TWI.ln	ln[topographic.wetness.index]	1977
2.4	TWI.ln	ln[topographic.wetness.index]	1999
3.1	year	drought.year	all
3.1	rp	ring.porosity	1999
3.2	PLA_dry_percent	percent.leaf.area	all
3.2	PLA_dry_percent	percent.leaf.area	1966
3.4	mean_TLP_Mpa	mean.turgor.loss.point	all

Table 3: Best full models for each drought scenario

best_model	scenario
resist.value ~ position_all+height.ln.m+TWI.ln+year+PLA_dry_percent+mean_TLP_Mpa+(1 sp/tree)	all droughts
resist.value ~ height.ln.m+rp+PLA_dry_percent+(1 sp)	1964-1966
resist.value ~ TWI.ln+rp+mean_TLP_Mpa+(1 sp)	1977
resist.value ~ position_all+height.ln.m+TWI.ln+rp+PLA_dry_percent+(1 sp)	1999

## Discussion

*1. paragraph summarizing main results → primary conclusions* When including only biophysical traits, trees' resistance value (on a per-species basis) is explained best by crown position and height, with codominant trees being the most resistant to drought. This follows on work done by (Bennett et al., 2015) [and others?] which show that larger trees suffer more during drought, and confirms that this susceptibility can be seen in tree ring analyses. Adding in crown position with the leaf hydraulic traits yields a slightly worse predictive model for drought tolerance, with height remaining as the only significant biophysical variable.

We partially supported the hypothesis that crown exposure makes trees more vulnerable to drought. Co-dominant trees had the highest drought resistance. Dominant trees had lower resistance, likely because they are the most exposed. Other studies have found clear evidence of greater drought sensitivity in trees with exposed crowns (e.g., (Suarez et al., 2004); (Scharnweber et al., 2019)). At the same time, intermediate and suppressed trees had even lower resistance. This indicates that other mechanisms such as competition or rooting depth were important. (Also note that our study design was not ideal for testing the role of canopy position. Current canopy position is a conservative separator of canopy position: trees may currently be in more dominant positions than they were at the time, but backwards movement is unlikely. This would bias against finding a significant effect for H1.2. Height may be a more reliable predictor of past canopy position than is current canopy position, and explains a portion of variation in canopy position.)

Proximity to stream—either vertical (elev) or horizontal (distance)—did not increase drought resistance; rather, it tended to decrease resistance (H1.3a). This may be because individuals growing further from water are acclimatized to drier conditions. However, the increase in drought resistance with distance from stream was less for small than large trees (H1.3b), indicating a potential importance of root depth/volume in conferring drought resistance.

**misc content to integrate** From (Kannenberget al., 2019), species with diffuse porous wood anatomy (*Liriodendron*) are more sensitive to drought, whereas ring-porous are not as affected because they more

easily rebuild structures for hydraulic conductivity. This paper mentions it would be good to have this data with respect to latent affects from drought. ### Conclusion

words

## Supplementary Information

### SCBI ForestGEO Plot

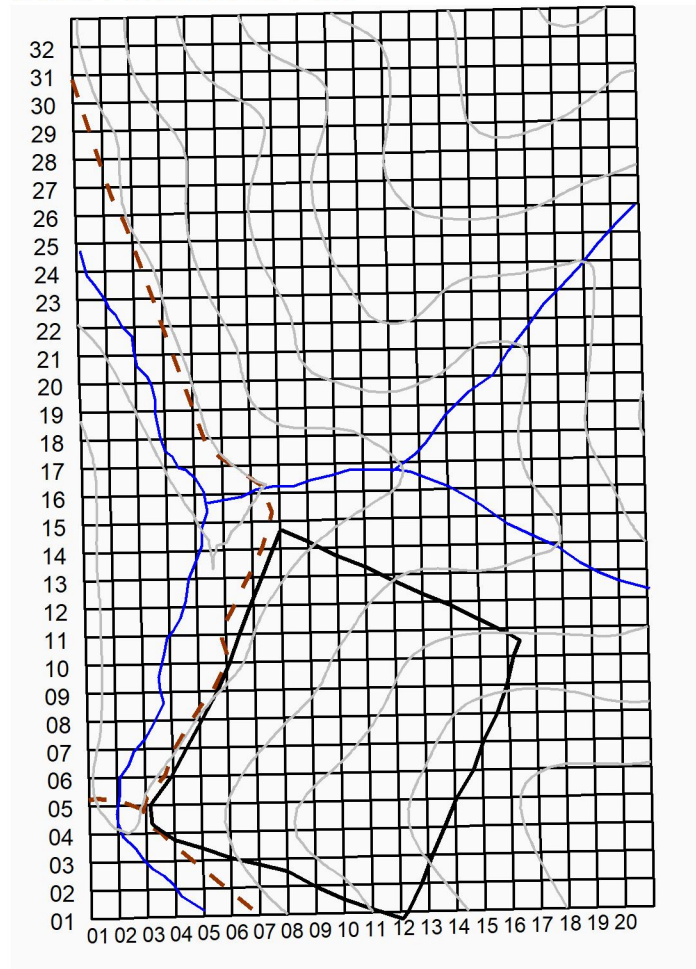


Figure 3: Map of ForestGEO plot

*p50 and p80* We decided to include values of P50 and P80 in the leaf traits model, defined by (Anderegg et al., 2016) as the water potentials at which a species loses 50% and 88% [80% by proxy], respectively, of hydraulic conductivity. Values were calculated by (**insert new methods here??**), and were only available for six species (*C. glabra*, *L. tulipifera*, *Q. alba*, *Q. prinus*, *Q. rubra*, and *Q. velutina*). Because of this, the model runs were considered to be incomplete due to the exclusion of the other 8 species. Results revealed neither p50 nor p80 to be significant, thus for the full analysis we decided to drop the two traits in order to include all species in the full analysis.

(see Issue #32)

**include TWI by trait graphs (2) here**

Table 4: Species-specific height regression equations

Species	Equations	r. <sup>2</sup>
<i>Carya cordiformis</i>	0.348+0.808*x	0.879
<i>Carya glabra</i>	0.681+0.704*x	0.855
<i>Carya ovalis</i>	0.621+0.722*x	0.916
<i>Carya tomentosa</i>	0.776+0.701*x	0.894
<i>Fagus grandifolia</i>	0.708+0.662*x	0.857
<i>Liriodendron tulipifera</i>	1.32+0.524*x	0.761
<i>Quercus alba</i>	1.14+0.548*x	0.647
<i>Quercus prinus</i>	0.44+0.751*x	0.869
<i>Quercus rubra</i>	1.17+0.533*x	0.773
all	0.879+0.634*x	0.857

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